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# DISTRIBUTION OF METEORITIC DEBRIS ABOUT THE ARIZONA METEORITE CRATER

*by* John S. Rinehart

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# Distribution of Meteoritic Debris About the Arizona Meteorite Crater[1]

By John S. Rinehart[2]

The meteorite crater in northern Arizona, an outstanding topographic feature of the earth's surface, is the earth's largest authenticated meteorite crater. It is a large bowl-like depression lying in a sandy semiarid region of northern Arizona which is readily accessible by car. In outline, the crater is a rough square, about 4,100 feet across and 600 feet deep, with an elevated rim rising 160 feet above the surrounding plain.

The crater has been well known since 1870. By 1909 it had been exhaustively described (Gilbert, 1896; Barringer, 1905, 1909; Tilghman, 1905; Merrill, 1908) and most serious investigators agreed with the view that it had been blasted out by the impact of a large meteorite. Numerous surveys have been made since then with various objectives. The chief surveys were those of Barringer (1914) and Barringer, Jr. (1927), who were intent upon locating and, if possible, recovering the large meteorite that made the crater; and of Nininger (1951; 1956).

In a recent book Nininger (1956) has given an excellent description of the researches and surveys made since the discovery of the crater, and has critically reviewed all of the findings to date. He also speculates on the nature of the event that took place at the time of the earth's encounter with the meteorite. When did it strike? How fast was it moving? From what direction did it come? How large was it? Was it a single large meteorite or a swarm of meteorites? Speculations of Barringer (1914), Nininger (1956), and others are inconclusive in many instances because of the great paucity of data.

The object of the survey reported here was to make a careful, systematic investigation of the distribution of the minuscule bits and pieces of meteoritic material that are scattered through the mantle of soil surrounding the crater, with a view to fixing more closely the mass of the meteorite that made the crater and its direction of flight. Our study arose from a suggestion by Nininger (1951), whose exploratory survey of the distribution of this material indicated that the amount might total several thousand tons, a weight many times greater than the 20 to 30 tons of meteorites that have been picked up in the surrounding territory thus far.

To carry out this survey, the Smithsonian Astrophysical Observatory sent an expedition into the field during the summer of 1956. This paper describes the results obtained.

## Processing the soil sample

The expedition collected and processed some 700 soil samples. Developing techniques to extract the meteoritic material from the samples was a major problem. Nininger's method had employed a magnet, dragged through the soil. The adhering magnetic material was then collected from the magnet and separated by hand, or by the use of an inclined surface which divided spherical particles from those of more irregular shape. A disadvantage of this technique is that it collects both weakly and strongly magnetic material, although none of the weakly magnetic material has been found

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[1] This work was partially supported by Contract No. AF19(604)-1901 with the Geophysics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command.

[2] Smithsonian Astrophysical Observatory and Harvard College Observatory, Cambridge, Mass.

to be of meteoritic origin. Such material, for example, never gives a positive test for nickel.

Since it seemed unwise to collect such material even in a preliminary extraction, and since we were interested only in the total amount of meteoritic material present whether its shape was flaky, chunky, or spheroidal, we did not use Nininger's method, but developed a special magnetic separator which is shown schematically in figure 1.

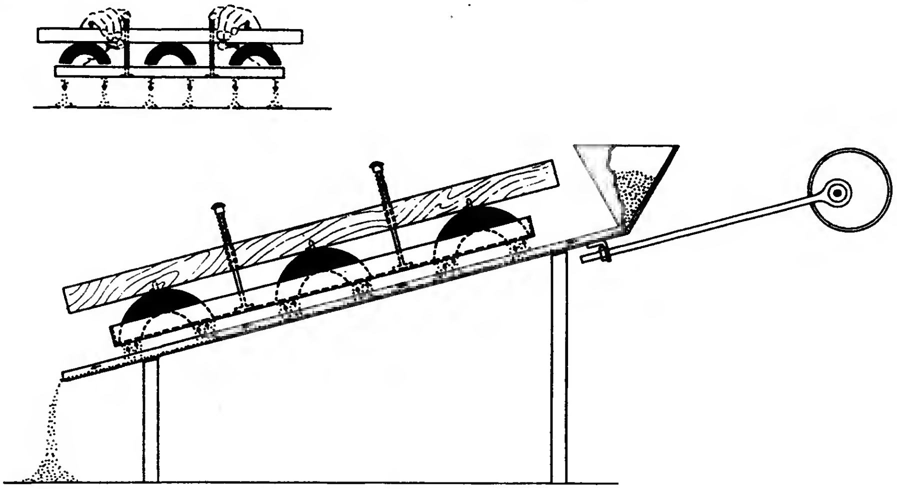

FIGURE 1.—Magnetic separator, shown schematically.

The separator consists basically of a vibrating hopper and a slanted trough down which the soil moves under the combined action of gravity and vibration. The trough is about one inch wide and two feet long. Three strong alnico magnets are suspended above the trough. As the soil moves downward, the magnetic material flies up and adheres to the suspended magnets. This method readily differentiates between weakly and strongly magnetic material, for the separation between magnet and trough is adjusted so that only the strongly magnetic material flies up. This technique worked especially well in the present instance because the unwanted constituents were, for the most part, only weakly magnetic and the line of demarkation between the two was very pronounced.

Various criteria for choosing the amount of soil to be processed were considered, and we fixed on a volume weighing about 2,000 grams on the average, as best, although individual samples sometimes varied by several hundred grams. This volume of dirt can be put conveniently into two paper quart containers, and was found to contain amounts of meteoritic material entirely adequate for the determinations. In taking a sample, we first scraped away about an inch of surface dirt, vegetable matter, and rocks, and then with a shovel scooped up enough soil to fill our containers. Each sample was labeled at the site and brought back to the laboratory where we separated it into four groups according to size by shaking it down in a series of U. S. Standard Sieves, Numbers 10, 40, and 100, which yielded four components. These sieves, which are commonly used for soil analysis, are made from woven wire mesh; the No. 10 sieve is woven with ten fairly coarse wires per inch; the No. 100 with 100 fine wires per inch.

All material larger than 2 mm in diameter was caught on the No. 10 sieve; this fraction contained stones, clods of dirt, vegetable matter, etc., and was always discarded. Some meteoritic material was lost in this way; its amount is roughly estimated in a later section. The material that passed the No. 10 sieve and was caught on the No. 40, referred to here as size 40 material, was between 2 mm and 0.42 mm in diameter, about the size of coarse sand. To be caught on the No. 100 sieve the particles (referred to henceforth as size 100) must be as large as 0.149 mm in diameter. The residue, or size "pan" particles, were then all less than 0.149 mm in diameter. The No. 10 fraction averaged 17 percent by weight of the sample. The remainder of the material was usually divided approximately equally among the other three fractions. During the early stages of the program, each of these was run through the magnetic separator individually.

The sieving accomplished two things: it insured that large particles of soil or sand did not seriously interfere with the extraction of small magnetic particles while being processed in the separator; and it enabled us to study the relative abundances of nonmeteoritic magnetic materials, which, from our point of view, were contaminants.

The magnets collected three types of strongly magnetic material: a meteoritic particle that consisted mostly of nickel-iron; a meteoritic iron-oxide particle; and a black, shiny particle. In addition, many particles were a cross between the first two types: patches or veins of iron-oxide would contain bits of unoxidized iron. Some dirt and a thin layer of yellow limonite adhered to the meteoritic particles. The black, shiny particles were probably bits of magnetite. The three types are most easily identified by mounting them in plastic and then grinding the plastic so that the particles are seen in cross-section. The copper from a copper sulfate solution plates out immediately on the iron particles so that these can easily be distinguished from iron-oxide particles although both have a metallic lustre. The relative percentages of each type of material varied among the size groups.

The meteoritic particles had various shapes: flakes, angular chunks, and ball-like masses. No very serious attempt was made to classify them because Nininger (1956) has already done so well in this regard. A portion of each sample was mounted in plastic, and many of the specimens were polished and inspected to make sure that the contents of each sample were principally meteoritic.

About one particle in every ten of the size 40 group was wholly nickel-iron in samples whose concentration of meteoritic material was high. This ratio varied a great deal however from sample to sample. Only a few particles were of the black, shiny type; the amount of this contaminant was much greater in the smaller sizes, with the No. 100 component containing about 15 percent. The "pan" material was found to be so highly contaminated that we could not determine the exact amount of meteoritic material present, but examination under a microscope showed that meteoritic fragments formed an exceedingly small percentage of the total magnetic component.

The correlation between the percentage of meteoritic debris in the finer material (size 100) and that in the coarser material (size 40) was found to be quite good; values for a number of representative samples are plotted in figure 2.

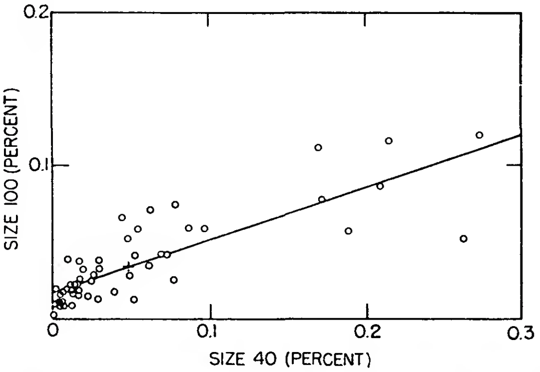

FIGURE 2.—Correlation between percents of size 100 and size 40 materials. Each point represents an individual sample. Ordinate is the percentage of size 100 material in the sample; abscissa is the percentage of size 40 material.

The abscissa is the percent by weight of meteoritic material in the size 40 component of soil; and the ordinate, the percentage in the size 100 component of the same sample. On the average, the concentration in the size 40 fraction is seen to be roughly two and one-half times that in the size 100 fraction. A similar plot of size "pan" versus size 40 showed only a very slight correlation between the two, indicating that a high percentage of the pan magnetic material was nonmeteoritic. Usually, although not always, the nickel test was negative with the pan material.

## Sampling procedure

The objective of the expedition was to sample the entire area surrounding the crater and thus determine as accurately as feasible the distribution of meteoritic debris. Many factors influenced the manner of sampling and the number of samples made. Because of limited time and funds, we decided to sample sparsely over a wide area rather than intensively over a small region, and to take mainly surface samples, relying on a few representative holes for an indication of the vertical distribution of material. We were anxious that our sampling area be large enough so that at its periphery the concentration of meteoritic material would be negligible. Our procedure was to begin in areas where we knew the concentration to be high and work out from these as far as we needed to.

Approximately 700 samples were taken from the locations shown in figure 3. The pattern is roughly a grid of 80 square miles with the crater near its center. The locations were separated by a distance of one-half mile. In the early phases of our work we occasionally took several samples at a single location, to check reproducibility of results or for other purposes; in general, however, we took two samples, about 30 feet apart. Each of these two samples was processed individually in order to obtain a rough indication of the local variation or irregularity in concentration. The two values were averaged for most purposes.

With the first 60 or 70 samples, we processed all fractions, except the size 10. It soon became clear, however, that processing the "pan" gave no reliable information because it was highly contaminated with nonmeteoritic material so this was abandoned. For most samples, therefore, meteoritic material was recovered only from the size 40 and size 100 fractions.

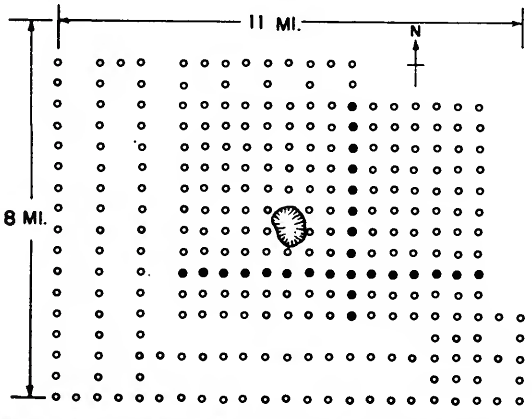

FIGURE 3.—Locations of sampling points. The crater is indicated at center. Open circles indicate surface points; solid circles, holes dug.

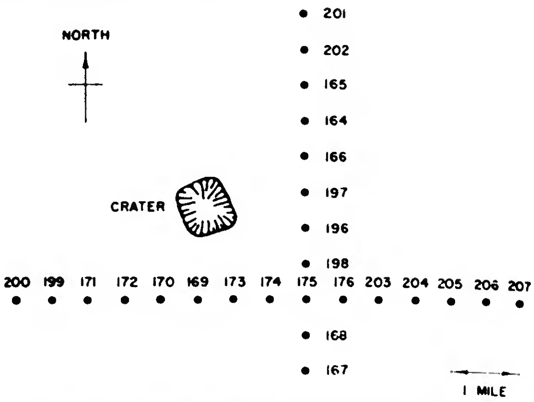

FIGURE 4.—Locations and sample numbers of holes dug.

The first step in processing was the careful weighing of each soil fraction. The magnetic component extracted from each fraction was weighed on an analytical balance and the percentage of meteoritic material computed. These percentages are listed in table 1 for all size 40 and size 100 samples; figure 9 shows their locations.

To study the vertical distribution of material, we dug to bedrock at 25 locations, shown in figure 4, and sampled the soil every few inches along the wall of the hole. Great care was taken not to contaminate a sample with dirt from some other part of the hole. The two lines of holes were chosen so as to traverse areas that could be considered representative of the whole region over which surface samples were taken. Bedrock was usually only one to three feet below the surface. In most holes the amount of meteoritic material decreased rapidly with depth in an approximately exponential fashion. In a few holes the concentration remained about constant from top to bottom. The distribution within each hole is shown in figure 5. Detailed data are listed in table 2.

### Estimate of total mass of meteoritic material

The data obtained provide the basis for estimating the total quantity of meteoritic material around the crater. Such an estimate suggests a minimum value for the mass of the meteorite that produced the crater. The percentages of size 40 magnetic material are the

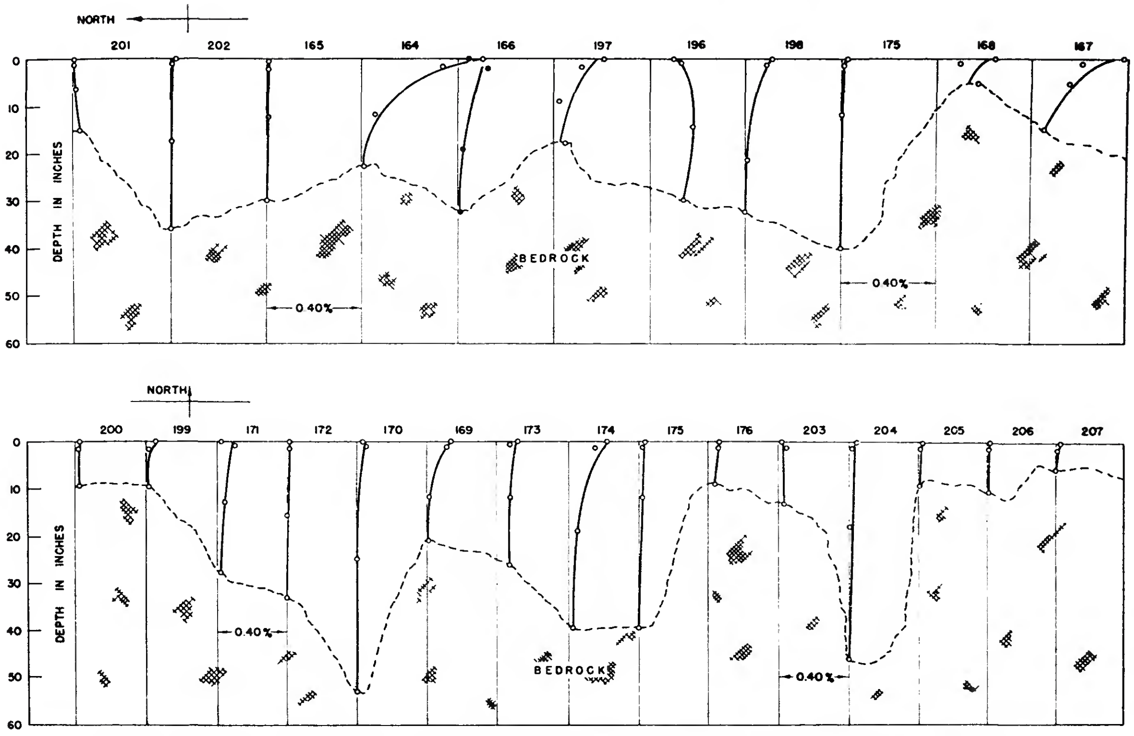

FIGURE 5.—Vertical distribution of meteoritic debris in each hole; sample numbers are given at the top.

most reliable, and we have therefore used them throughout as primary data.

To estimate the total weight, $W$, we evaluate the integral

$$W=\int_v \rho_m dV \tag{1}$$

where $\rho_m$ is the density (gm/cc or lb/ft$^3$) of meteoritic material. This density of course varies from point to point. The volume over which the integration is carried out is the mantle of soil around the crater.

Certain assumptions and a number of approximations, some very good and others quite rough, must be made in order to carry out the integration.

First, we establish a standard soil sample. By weight this sample consists of 17 percent size 10 fraction, 25 percent size 40 fraction, 30 percent size 100, and 28 percent size "pan." These percentages were obtained by averaging values from the 700 samples taken.

Second, we assume that *in situ* the soil has a void ratio of 1/3 so that the volume, $V$, occupied by soil of mass $S$ is given by

$$V=\frac{3}{2}\frac{S}{\rho} \tag{2}$$

where $\rho$ is the average density of the soil particles themselves. Since the soil is mostly quartz sand we take $\rho$ equal to 2.65 gm/cc or $2.65\times62.4$ lb/ft.$^3$

Third, since the size 10 magnetic component was not measured and the size 100 and size "pan" were unduly contaminated with nonmeteoritic material, we must infer the amounts of size 10, size 100, and size "pan," from determination of the amount of size 40 meteoritic material. The amount of size "pan" was taken as zero since there was so little correlation between size 40 and size "pan." The amount of size 100 component, as indicated in figure 2, averaged about 0.4 that of size 40. The size 10 fraction of soil usually consisted of small clods of dirt which broke up into sizes 40, 100, and "pan" when crushed. Hence we assumed that the amount of meteoritic material could best be approximated by taking it as equal to the average of the other three components. Summarizing, we have

$$m_p=0$$

$$m_{100}=0.4\ m_{40}$$

$$m_{10}=\frac{m_p+m_{40}+m_{100}}{3}=\frac{(0+1+0.4)}{3}\ m_{40}=0.5\ m_{40}$$

where $m_p$ is the mass of size "pan" meteoritic material in the sample of total mass $S$; $m_{40}$, the mass of size 40; $m_{100}$, the mass of size 100; and $m_{10}$, the mass of size 10. Our final estimate for the total mass, $m$, of meteoritic material in a soil sample of mass $S$ is the sum of the masses of the individual fractions or

$$m=1.9\ m_{40}$$

Now, as mentioned above

$$S_{40}=0.25\ S$$

where $S_{40}$ is the mass of the size 40 fraction of the soil so that

$$m=0.5\,\frac{m_{40}}{S_{40}}\,S. \qquad (3)$$

Combining equations (1), (2), and (3) we have

$$W=\int 0.5\left(\frac{m_{40}}{S_{40}}\right)\left(\frac{2}{3}\,\rho\right)dV \qquad (4)$$

which can be integrated if we know only the ratio, $m_{40}/S_{40}$, for each point.

Fourth, while this ratio is well established at the surface of the soil mantle, we need to make some assumptions regarding the variation with depth. The vertical distribution of meteoritic material within the holes shows that the density decays roughly exponentially with depth and is reasonably well represented by the equation

$$\rho_m=\rho_{m_0}{}^{-1.44y} \qquad (5)$$

where $\rho_{m_0}$ is the density of meteoritic material at the surface and $y$ is distance in feet below the surface. The constant in the exponent was chosen so that $\rho_m$ would be equal to $\frac{1}{2}\rho_{m_0}$ for $y=\frac{1}{2}$ ft. The choice is in good accord with the observations made in the 25 holes.

Fifth, we assume that the average depth of the mantle is two feet. The exact depth is not critical because the density of meteoritic material falls off so rapidly with depth; at two feet it is only 0.06 the surface density. The average density, $\rho_{m_{av}}$, in a mantle of this depth is

$$\rho_{m_{av}}=\frac{1}{2}\int_0^\infty \rho_{m_0} exp^{-1.44y}dy=\frac{1}{2.88}\,\rho_{m_0}. \qquad (6)$$

With these assumptions we can now perform the integration. We have according to equation (4)

$$W=0.5\left(\frac{2}{3}\,\rho\right)\sum\left(\frac{m_{40}}{S_{40}}\right)_i V_i \qquad (7)$$

where $\left(\frac{m_{40}}{S_{40}}\right)_i$ is the average value of the ratio for the volume element $V_i$ of the mantle. Now $V_i$ can be replaced by $2A_i$ where $A_i$ is a surface element of the mantle expressed in square feet and $\left(\frac{m_{40}}{S_{40}}\right)_i$ can be replaced by $\frac{1}{2.88}\left(\frac{m_{40}}{S_{40}}\right)_{s_i}$ where the subscript $s$ denotes the surface value of the ratio. Substituting these values into equation (7) we have the weight in pounds,

$$W=0.5\times2\times\frac{1}{2.88}\times\frac{2}{3}\times2.65\times62.4\sum\left(\frac{m_{40}}{S_{40}}\right)_{s_i}A_i$$
$$=38.2\sum\left(\frac{m_{40}}{S_{40}}\right)_{s_i}A_i.$$

The value of the summation is most easily computed from the chart in figure 6 which gives average values of the ratio for segments of area. We find that

$$\sum\left(\frac{m_{40}}{S_{40}}\right)_{s_i}A_i=6.46\times10^5\ \text{ft}^2.$$

Substituting, we have

$$W=38.2\times6.46\times10^5$$
$$=24.7\times10^6\ \text{lb},$$

or

$$=12{,}000\ \text{tons}.$$

Thus the total amount of finely divided meteoritic material present in the soil is about 12,000 tons. However, this figure is subject to a still further uncertainty. We noted that about 90 percent of the meteoritic material that we collected is iron-oxide, $Fe_3O_4$, and contained 27.6 percent oxygen by weight. Thus, about one-quarter of the above estimated mass is very likely terrestrial oxygen that combined with the meteoric iron after its encounter with the earth.

Further, there seems to be no way to allow precisely for the amount of contaminating material present. Increasing the area of the soil mantle over which the integration was taken enlarges the error caused by contamination since in the outlying regions the ratio between contaminant and meteoritic material becomes ever larger. We have tried to choose an area that minimizes the effects of contaminants but at the same time includes almost all of the meteoritic material. It will be noted, however, that even for the area chosen, the density of magnetic material falls off less rapidly than $1/r^2$ ($r$ equals distance from center of crater) and the integral does not converge. At distances of over about two miles from the crater the percentages given on the chart are little if any higher than the background contamination which on the average ranged from 0.002 to 0.005 percent. To obtain a true measure of the meteoritic material, the percentage in each segment should be reduced by this amount. When this is done our computed mass of 12,000 tons is reduced by about 10 to 20 percent.

## Distribution of meteoritic debris

The distribution pattern of the meteoritic debris around the crater is shown in figure 7, based on the data for the size 40 material

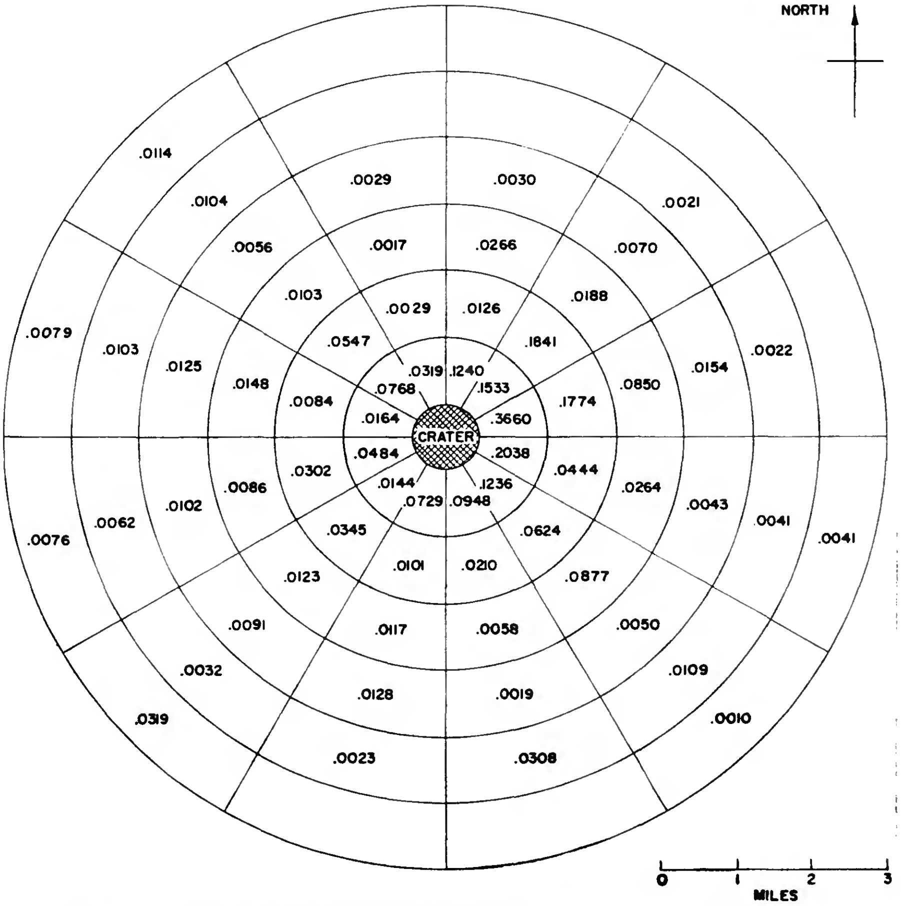

FIGURE 6.—Average percentages of size 40 meteoritic material in the soil around the crater.

(given in table 1). The contour lines show areas having equal densities of debris; the solid lines represent 0.1 percent changes. The broken lines indicate the 0.05 percent level.

The chart indicates several things. First, the debris itself lies in a perfectly definite pattern. Second, the crater itself does not lie at the center of the pattern. Third, the debris is symmetrically distributed about a line that runs somewhat north of east. Its exact position is hard to fix more specifically from our data, but the outside limits are due east and 45° north of east. Fourth, the distribution, while symmetrical, is not smooth, but contains several local areas in which the density of meteoritic material is high. And, fifth, there is a concentration of material to the east of the crater.

Although the definite pattern of debris was not surprising, it was encouraging, for it represents evidence that our data were not seriously distorted by sample contamination with terrestrial magnetic material. The symmetry of the pattern, its relationship to the crater, and the localization of material are our most significant results, and will be discussed later.

It is interesting to speculate on how the meteoritic debris reached the points where it is found today. The two chief hypotheses are: the material fell to its present location shortly before, just at, or shortly after, the instant of the meteor's impact; or the material was deposited, after the impact, by the action of wind and water or other carriers. The very close similarity between the distribution of ponderable chunks of meteoritic material, as shown in Barringer's (1909) chart, and the distribution of minute pieces as determined by our survey, constitutes strong evidence pointing to the first as the most probable hypothesis.

Nininger (1956) has suggested that a strong wind was blowing at the time of the meteor's impact, and that the meteoritic debris represents condensation products from a vast metallic cloud rising vertically from the crater and distributed asymmetrically about the crater by the wind. Our survey does not support this theory,

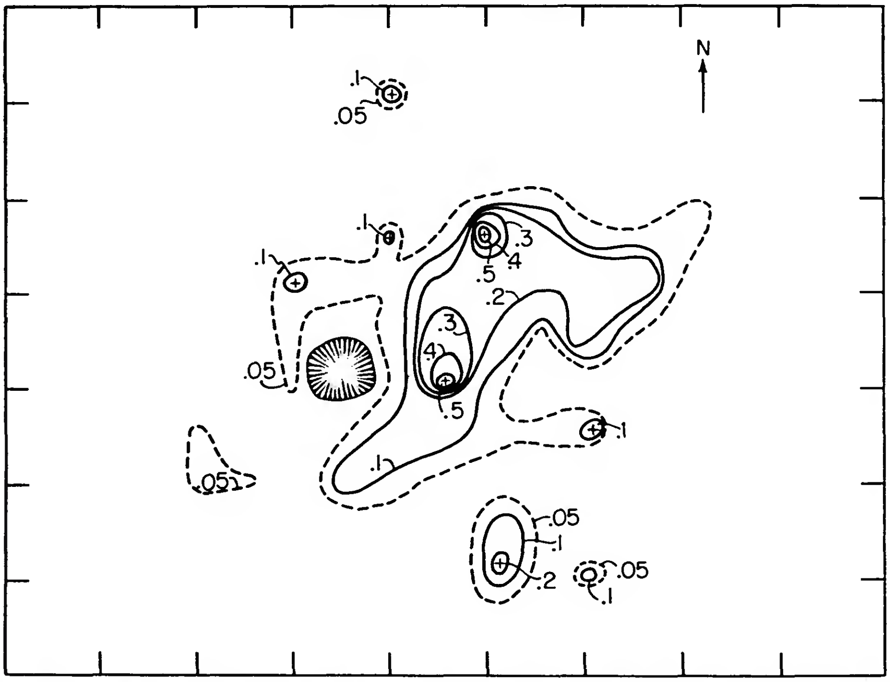

FIGURE 7.—Distribution pattern of meteoritic debris around the crater. Contour lines indicate areas of equal density, given in percents; solid lines represent 0.1 percent changes; broken lines indicate the 0.05 percent level.

however; it is not easy to imagine a wind strong enough to propel large chunks and minute pieces of the same material in exactly the same direction and for the same distance. The present juxtaposition of the two classes of material while not irrefutable evidence, certainly strongly suggests that both were deposited at the same time, and that any subsequent shifting by the wind has been negligible. Many of the bits are probably remnants of ponderable chunks.

Shifting of the material by the wind over the centuries is a reasonable thing to postulate, and, in fact, the direction of the observed asymmetry is that of the prevailing wind. Another possibility which must be considered is that the vaporized metal condensed in droplets which fell with radial symmetry about the crater and were subsequently blown northeasterly by the wind. The asymmetrical distribution of the large chunks, however, cannot be explained on this basis. If wind were a factor we might expect that the bits would be sorted by weight; no evidence of such a sorting was found.

A highly reasonable hypothesis is that the meteorite approached the earth from a southwesterly direction and, when it struck, pitched forward large quantities of meteoritic material to the position where it now rests. (Such a shoveling action occurs frequently with obliquely impacting high speed missiles.) Orbital arguments do not favor any particular direction of encounter except possibly east-west (or west-east) slightly over north-south (or south-north). When the meteorite struck it must have been almost completely shattered, into pieces that weighed from a thousand pounds or so downward. No piece larger than 2000 pounds has ever been found (Barringer, 1914) while thousands of smaller pieces weighing a few ounces or less have been recovered. Much melting and considerable vaporization would have accompanied this shattering. It seems unlikely, however, that much of the vaporized material would have condensed into metallic droplets. More probably, it would have oxidized and drifted off as a fine powder. On the other hand, the sprays of molten material would probably have moved along with the solid fragments so that deposition of molten (which of course would quickly solidify) and of solid fragments would have occurred at the same time.[3]

Eventually, of course, both forms of material would gradually have disintegrated, by a process of oxidation and subsequent exfoliation. The taenite, being more resistant to oxidation than the kamacite, would be the last to go. It is significant that Nininger finds that the metallic bits contain about 17 percent nickel, a composition compatible with that of taenite. Thus, one would expect to find in the soil minute pieces of both oxide and metallic matter, and even to find them intimately mixed. The observed variety in particle shape is likewise consistent with the view that these bits are, in the main, remnants of larger chunks of meteoritic material. The exact nature of the bits is still being intensively studied and they will be described in a later report.

The several local areas of high concentration indicate that the rain of meteoritic debris was spotty. Each area would then represent a region in which a large swarm of fragments fell after being ejected from the crater. This theory receives strong support from the data yielded by our pairs of samples. Recall that two samples, about 30 feet apart, were taken from each location; and the percentage of meteoritic material in the two often differed by a factor of two or three, and had no relation to local irregularities of terrain. Local wind eddies may have affected the distribution slightly. Such highly localized variation in the distribution indicates a second order patchiness of the ejecta that is entirely consistent with our knowledge of the phenomena of high speed impact.

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[3] E. P. Henderson, of the U. S. National Museum, after reading this paper in manuscript, made the following comment:

"Possibly the mass that made the crater had some satellite masses. These, being smaller, were retarded during the fall through our atmosphere, so possibly they fell outside the area of the crater. Being small, they did not make a crater. The crater-forming mass retained its velocity and was ablating until the moment of impact. Quantities of material were removed and carried into the turbulent wake of the meteorite. Since these pieces were small, their velocity was quickly lost. They should settle to the ground at a considerable distance short of the end point of the large crater-producing mass. It would seem that such material should be tracked almost up to the rim of the crater. On the opposite side and in line with the trajectory of the falling meteorite, one should get pieces that broke from the large meteorite and rocks that were tossed out of the crater. This point was stressed earlier in the paper."

**The direction of impact**

The fact that the meteoritic debris is distributed symmetrically about a line gives us the direction but not necessarily the sense of the trajectory of the meteorite. Experience with the effects of high speed impact shows that one can unambiguously associate symmetry of the ejected missile and impact debris with direction of impact. The axis of symmetry and the trajectory of the missile always lie in the same plane. The same situation must obtain here. Thus, if we assume that the debris now lies where it originally fell, then there is little doubt that the meteorite approached the earth along the axis of symmetry of our pattern: roughly, north of east or south of west.

Whether the approach was from the east or from the west is debatable. If the meteorite approached its point of impact at a steep angle from the east, shedding material as it neared the ground, deposited a substantial amount of debris to the east of the crater and then buried itself beneath the floor of the crater, it could now lie under the southwest corner of the crater. The assumption of a steep approach would be required to account for the fact that very little meteoritic material is found to the west of the crater although a large field of ejected boulders lies on this side. On the other hand, the meteorite could well have approached from the west and thrown debris forward, to the east, where we find an even greater accumulation of large fragmented limestone boulders and other ejecta than on the west. The boulders east of the crater have been thrown farther than on the west, in some cases two or three miles (Barringer, 1909, 1914). A western approach would not require us to assume so steep an angle of impact since we are now permitted to assume also that meteoritic material was thrown forward by the force of the impact. The evidence for a western approach is therefore the stronger.

Impactite and rock flour are other forms of ejecta (Merrill, 1908; Nininger, 1954). Impactite is sandstone metamorphosed by the intense heat of the impact, and impregnated with fine bits of meteoritic material and, occasionally, bits of limestone. Two large patches have been found, southeast and northwest of the crater. The sandstone from which this material was made lies deep in the crater. Rock flour is similar sandstone that was ground to fine powder at the time of impact. Large quantities lie within and piled more or less uniformly around the rim of the crater (Barringer, 1909). Large masses of meteoritic oxide and meteorites are occasionally found embedded in it. It is not at all obvious how the impactite and rock flour got to their present position. They probably were thrown out immediately after the limestone boulders and meteoritic debris were ejected, although it is difficult to demonstrate this conclusively.

The structures of recovered meteorites also suggest an approach from the southwest or west. Meteorites found to the east and northeast of the crater have been severely altered by heat and deformation. Those found far out on the plain to the southwest and west, however, are in their virgin state (Nininger, 1956), and may well be pieces that broke from the meteorite as it approached from the west. Usually these specimens are fairly large and are sparsely distributed.

Heretofore, it has been postulated that the meteorite approached from a north-northwesterly direction (Barringer, 1909, 1914; Nininger, 1956). This conclusion was based, at first, on a reconnaissance examination of the tilting of the rock strata; later, on extensive drillings made in the crater and on its south rim; and finally, on magnetic, electrical, and gravimetric surveys. These data are difficult to evaluate. Many investigators have attempted to do so and much of what has been written is naturally conjectural. The magnetic, electrical, and gravimetric surveys seem, in spite of some contradictory evidence, to favor a southwest to northeast direction. The observed anomalies, shown in figure 8 (from Nininger, 1956), are not pronounced but they all seem to lie either in or beyond the southwest part of the crater.

Barringer made extensive drillings over a long period of years, and thus established the fact that large masses of fragmented rock lie buried beneath the floor and south rim of the crater. Since drillings have not been made at other locations we have no way of knowing how much fragmented rock lies beneath the east, north, and west rims, and we know very little

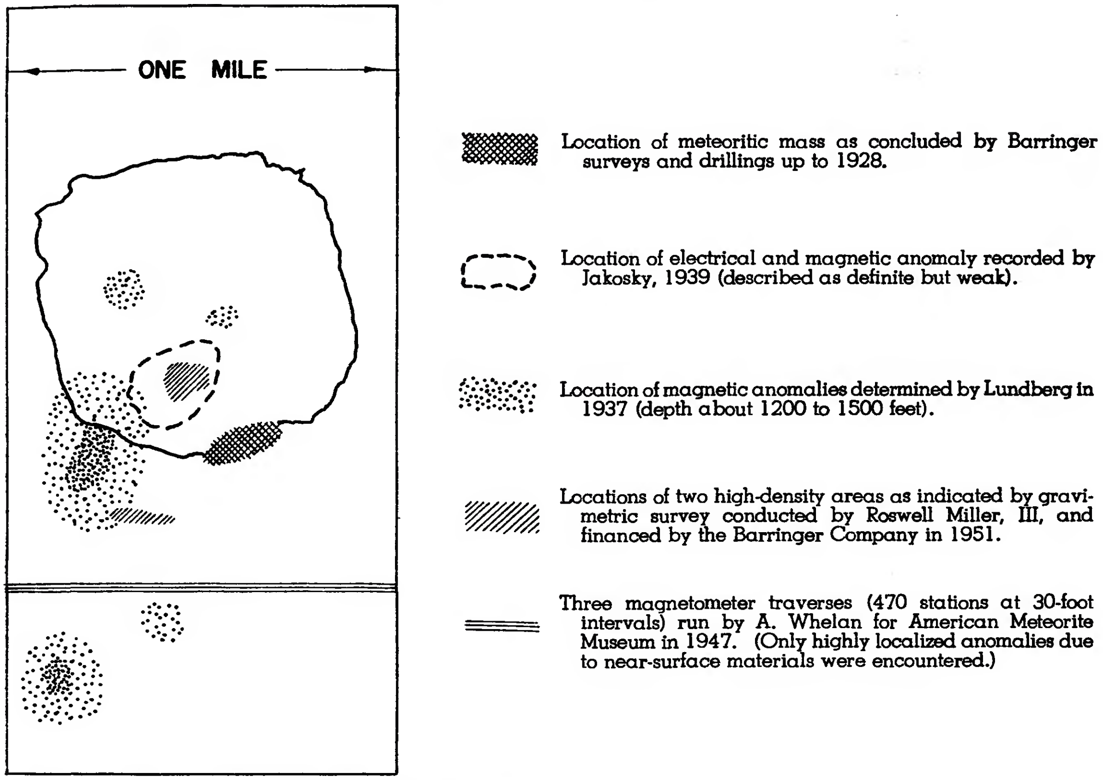

FIGURE 8.—Results of various geophysical surveys of crater.

about the shape of the subsurface region that was shattered by the impact. Further data on this point could be of very great help in establishing the direction of impact.

As well as we can determine, the only study of the tilting of strata was a reconnaissance surface examination made by Barringer (1909) whose findings have been summarized by Watson (1936):

> The least amount of tilt is found in the northern wall. The slope increases along both the eastern and western walls, until in the southeast and southwest the strata are practically vertical. In contrast to the strata so tilted, and separated from them by an abrupt discontinuity, there occurs, along the rim slightly east of south, a broad arch, 2,700 feet long, the almost flat strata of which have been raised vertically about 100 feet. The arch appears to be a localized uplift possibly due to steam explosion subsequent to the complete deceleration of the penetrating body. The peculiarity of the tilting combined with the rock structure beneath the crater, suggests that the impact was not vertical, as previously supposed, but at a considerable slant from the north.

To test this theory of the direction of impact, a churn-drill was put down through the center of the arch in the south rim of the crater wall. Below a depth of 1,200 feet the drill passed through a region increasingly rich in loose meteoritic material and finally stuck at 1,340 feet, a region very rich in nickel-iron and exceedingly resistant to boring. The drill was slowly forced through 30 feet of this material but it stuck and remains completely immovable at 1,376 feet. The behavior of the drill shows that the meteoritic penetration continued to a depth of over 1,300 feet and also that very probably a portion of the original mass lies buried beneath the southern rim of the crater. From the position of this mass, the various depths of the undisturbed strata under the crater, and the symmetrical tilting of the crater walls around the north-south axis, it was concluded by the Barringers and their associates that the body struck from the north and at an angle of approximately 45°.

It is hard to appreciate, however, what these tilt measurements do in fact signify. They show us only the condition at the surface and leave us completely in the dark as to how much tilting and faulting has occurred below the surface. Our best evidence on this point is the overall shape of the rim of the crater. The rim rises above the surrounding plain to a height, about 160 feet, which is almost the same at all points. The rock strata are completely exposed along the crest of the rim. The strata and the general area of the crater lie more or less horizontally although they dip slightly to the north. The uniformly high rim must mean that gross tilting and faulting are about the same all around the rim.

This situation is not surprising. At the meteorite's impact, one would expect the strata to fragment rather than to tilt, and tilting would be in the form of faulting, not bending, which can be accomplished only under slow application of load. Fragmentation or faulting would radiate out from the point of impact and would cease only when the stress of impact had decayed to a value less than the fracture strength of the rock. Oblique impact into a perfectly brittle, homogeneous, isotropic medium would produce no rim at all. In a plastic medium, such as steel, a flow of material would occur and a rim would be built up very asymmetrical in height which would be greatest on the side away from that of the missile's approach. The rim would possess a bilateral symmetry about a line parallel to the trajectory of the impacting missile.

In the case of the Arizona Meteorite Crater, the mechanical properties of the strata *in situ* must play an important role in influencing the configuration that the strata assume after impact (see Hager, 1953, for a detailed discussion of the strata). The general drift of the strata is in a northerly direction. It is reasonable to suppose that the mechanical properties of the strata *in situ* possess an anisotropy which is directly related to this northerly dip, and could easily cause a failure pattern of the rock to assume an east-west symmetry. The pattern

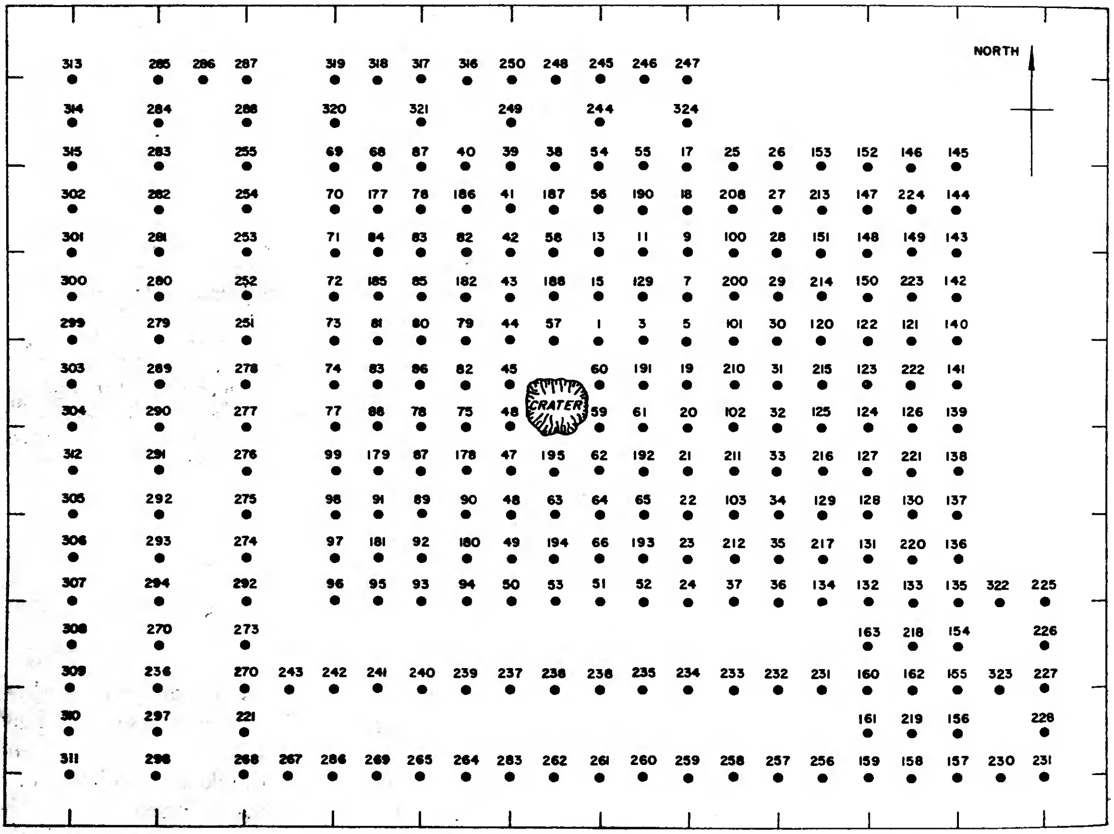

FIGURE 9.—Locations of all sampling points. Distance between grid lines: 1 mile.

might therefore bear little relationship to the direction of the impact.

Our argument here leaves much to be desired in the way of completeness. It is indeed unfortunate that we have so little experimental data on these matters.

## Evidence for large buried mass

The data presented here give no direct indication as to whether a large mass of meteoritic material lies buried in the crater. If one accepts the low estimates, 10,000 to 15,000 tons (Rinehart, 1950; Wylie, 1943) of the mass needed to form the crater then no large mass could possibly remain. If, on the other hand, one accepts the 5,000,000 ton estimate of Öpik (1936) and of Rostoker (1953) as more realistic, then the amount of meteoritic debris so far recovered is insignificant and a large mass could well lie buried. According to F. L. Whipple (personal communication), a most reasonable mass is that given recently by Hill and Gilvarry (1956), between 80,000 and 400,000 tons.

TABLE 1.—*Horizontal surface distribution of meteoritic material*

| Location of sample (see fig. 9) | Percent by weight of magnetic material | | | | | |
|---|---|---|---|---|---|---|
| | Size 40 | | | Size 100 | | |
| | In samples | | Average | In samples | | Average |
| 1 | .078 | .076 | .077 | .025 | .026 | .026 |
| 3 | .206 | .211 | .208 | .077 | .096 | .086 |
| 5 | .328 | .218 | .273 | .136 | .104 | .120 |
| 7 | .303 | .838 | .570 | .089 | .112 | .100 |
| 9 | .004 | .004 | .004 | .018 | .014 | .016 |
| 11 | .012 | .032 | .022 | .011 | .019 | .015 |
| 13 | .022 | .009 | .016 | .019 | .011 | .015 |
| 15 | .230 | .112 | .171 | .097 | .057 | .077 |
| 17 | .0119 | .0166 | .0142 | .0198 | .0262 | .0230 |
| 18 | .0331 | .0199 | .0265 | .0334 | .0245 | .0290 |
| 19 | .0532 | .2840 | .1686 | .0779 | .1434 | .1106 |
| 20 | .0580 | .0633 | .0606 | .0332 | .0351 | .0342 |
| 21 | .1090 | .0478 | .0779 | .0865 | .0606 | .0736 |
| 22 | .0129 | .0063 | .0096 | .0268 | .0119 | .0194 |
| 23 | .2960 | .0796 | .1878 | .0575 | .0566 | .0570 |
| 24 | .1565 | .3660 | .2612 | .0456 | .0591 | .0524 |
| 25 | .0047 | .0029 | .0038 | .0111 | .0107 | .0109 |
| 26 | .0023 | .0020 | .0022 | .0098 | .0126 | .0112 |
| 27 | .0055 | .0024 | .0040 | .0244 | .0150 | .0197 |
| 28 | .0075 | .0054 | .0064 | .0209 | .0135 | .0172 |
| 29 | .0332 | .0753 | .0542 | .0522 | .0637 | .0580 |
| 30 | .1876 | .6300 | .4088 | .2050 | .5490 | .3770 |
| 31 | .2820 | .1456 | .2138 | .1298 | .1020 | .1159 |
| 32 | .0412 | .0169 | .0290 | .0162 | .0093 | .0128 |
| 33 | .1105 | .0833 | .0969 | .0651 | .0541 | .0596 |
| 34 | .0502 | .0447 | .0474 | .0463 | .0569 | .0516 |
| 35 | .0011 | .0033 | .0022 | .0175 | .0269 | .0222 |
| 36 | .0800 | .0914 | .0857 | .0570 | .0604 | .0587 |
| 37 | .0400 | .0488 | .0444 | .0723 | .0606 | .0664 |
| 38 | .0013 | .0015 | .0014 | .0097 | .0059 | .0078 |
| 39 | .0008 | .0006 | .0007 | .0018 | .0067 | .0042 |
| 40 | .0030 | .0026 | .0028 | .0292 | .0063 | .0178 |
| 41 | .0022 | .0021 | .0022 | .0088 | .0072 | .0080 |
| 42 | .0066 | .0031 | .0048 | .0113 | .0261 | .0187 |
| 43 | .0002 | .0020 | .0011 | .0008 | .0019 | .0014 |
| 44 | .0561 | .1568 | .1064 | .0125 | .0107 | .0116 |
| 45 | .0741 | .0707 | .0724 | .0124 | .0417 | .0270 |
| 46 | .1295 | .0053 | .0674 | .0184 | .0084 | .0134 |
| 47 | .0059 | .0236 | .0148 | .0061 | .0212 | .0136 |
| 48 | .0277 | .0366 | .0322 | .0251 | .0128 | .0190 |
| 49 | .0115 | .0195 | .0155 | .0181 | .0246 | .0214 |
| 50 | .0022 | .0008 | .0015 | .0027 | .0059 | .0043 |
| 51 | .0611 | .0123 | .0367 | .1190 | .0062 | .0626 |
| 52 | .0056 | .0032 | .0044 | .0264 | .0039 | .0152 |
| 53 | .0236 | .0218 | .0227 | .0845 | .0502 | .0674 |
| 54 | .0700 | .1007 | .0854 | .0267 | .0588 | .0428 |
| 55 | .0069 | .0035 | .0052 | .0145 | .0130 | .0138 |
| 56 | .0054 | .0065 | .0060 | .0058 | .0130 | .0094 |
| 57 | .0949 | .0789 | .0869 | .0624 | .0054 | .0314 |
| 58 | .0023 | .0055 | .0039 | .0032 | .0023 | .0028 |
| 59 | .0254 | .0333 | .0294 | .0214 | .0064 | .0139 |
| 60 | .1124 | .0850 | .0987 | .0204 | .0042 | .0123 |
| 61 | .6280 | .4150 | .5215 | .0217 | .1395 | .0806 |
| 62 | .1348 | .1922 | .1635 | .0197 | .0530 | .0364 |
| 63 | .1655 | .1438 | .1546 | — | — | — |
| 64 | .0607 | .1290 | .0948 | .0542 | .1200 | .0871 |
| 65 | .0456 | .0361 | .0408 | .0230 | .0309 | .0270 |
| 66 | .0072 | .0073 | .0072 | — | .0106 | — |
| 67 | .0004 | .0002 | .0003 | .0047 | .0010 | .0028 |
| 68 | .0020 | .0013 | .0016 | .0017 | .0017 | .0017 |
| 69 | .0014 | .0015 | .0014 | .0264 | .0153 | .0208 |
| 70 | .0206 | .0154 | .0180 | .0483 | .0157 | .0320 |
| 71 | .0160 | .0175 | .0168 | .0146 | .0389 | .0268 |
| 72 | .0064 | .0062 | .0063 | .0112 | .0214 | .0163 |
| 73 | .0147 | .0146 | .0146 | .0203 | .0228 | .0216 |
| 74 | .0332 | .0138 | .0235 | .0155 | .0347 | .0251 |
| 75 | .0276 | .0311 | .0294 | .0507 | .0257 | .0382 |
| 76 | .0089 | .0005 | .0047 | .0124 | .0037 | .0080 |
| 77 | .0046 | .0027 | .0037 | .0148 | .0202 | .0175 |
| 78 | — | — | — | — | — | — |
| 79 | .0874 | .0120 | .0497 | .0418 | .0140 | .0279 |
| 80 | .0100 | .0063 | .0082 | .0126 | .0264 | .0195 |
| 81 | .0136 | .0110 | .0123 | .0118 | .0208 | .0163 |
| 82 | .0012 | .0014 | .0013 | .0085 | .0078 | .0082 |
| 83 | .0062 | .0094 | .0078 | .0459 | .0332 | .0396 |
| 84 | .0076 | .0007 | .0042 | .0107 | .0107 | .0107 |
| 85 | .0128 | .0178 | .0153 | .0234 | .0314 | .0274 |
| 86 | .0124 | .0131 | .0128 | .0132 | .0262 | .0197 |
| 87 | .0561 | .0897 | .0729 | .0226 | .0627 | .0426 |
| 88 | — | — | — | — | — | — |
| 89 | .0765 | .0598 | .0682 | .0462 | .0402 | .0432 |
| 90 | .0169 | .0849 | .0509 | .0143 | .0097 | .0120 |
| 91 | .0453 | .0143 | .0298 | .0464 | .0206 | .0335 |
| 92 | .0124 | .0103 | .0114 | .0138 | .0303 | .0220 |
| 93 | .0053 | .0050 | .0052 | .0090 | .0130 | .0110 |
| 94 | .0005 | .0003 | .0004 | .0033 | .0007 | .0020 |
| 95 | .0144 | .0241 | .0192 | .0239 | .0404 | .0322 |
| 96 | .0203 | .0122 | .0162 | .0289 | .0082 | .0186 |
| 97 | .0108 | .0077 | .0092 | .0158 | .0248 | .0203 |
| 98 | .0030 | .0094 | .0062 | .0111 | .0086 | .0098 |
| 99 | .0191 | .0128 | .0160 | .0621 | .0126 | .0374 |
| 100 | .0411 | .0846 | .0628 | .0434 | .0995 | .0714 |
| 101 | .3850 | .0611 | .2230 | .0299 | .0443 | .0371 |
| 102 | .0263 | .0177 | .0220 | .0274 | .0128 | .0201 |
| 103 | .0433 | .0322 | .0378 | .0214 | .0138 | .0176 |
| 104 | .0005 | .0000 | .0002 | .0002 | — | — |
| 105 | .0008 | .0004 | .0006 | .0004 | .0020 | .0012 |
| 106 | .0013 | .0026 | .0020 | .0000 | .0066 | .0033 |
| 107 | .0008 | .0002 | .0005 | — | .0004 | — |
| 108 | .0001 | .0004 | .0002 | .0005 | .0003 | .0004 |
| 109 | .0010 | .0029 | .0020 | .0011 | .0002 | .0006 |
| 110 | .0005 | .0084 | .0044 | .0005 | — | — |
| 111 | — | .0004 | — | .0005 | .0001 | .0003 |
| 112 | .0004 | .0008 | .0006 | — | .0030 | — |
| 113 | .0001 | .0006 | .0004 | .0008 | .0014 | .0011 |
| 114 | .0007 | .0003 | .0005 | .0004 | .0005 | .0004 |
| 115 | .0590 | — | — | .0009 | .0009 | .0009 |
| 116 | .0009 | .0005 | .0007 | .0012 | .0008 | .0005 |
| 117 | .0000 | .0005 | .0002 | .0001 | .0014 | .0007 |
| 118 | .0009 | .0003 | .0006 | .0005 | .0017 | .0011 |
| 119 | .0014 | .0005 | .0010 | .0106 | .0014 | .0060 |
| 120 | .0253 | .0313 | .0283 | .0096 | .0433 | .0264 |
| 121 | .0062 | .0051 | .0056 | .0018 | .0019 | .0018 |
| 122 | .0001 | .0019 | .0010 | .0024 | .0022 | .0023 |
| 123 | .0085 | .0095 | .0090 | .0209 | .0191 | .0200 |
| 124 | .0025 | .0098 | .0062 | .0028 | .0126 | .0077 |
| 125 | .0012 | .0012 | .0012 | .0023 | .0067 | .0045 |
| 126 | .0048 | .0019 | .0034 | .0038 | .0093 | .0066 |
| 127 | .0000 | .0035 | .0018 | .0011 | .0127 | .0069 |
| 128 | .0044 | .0008 | .0026 | .0029 | .0018 | .0024 |
| 129 | .0103 | .0281 | .0192 | .0391 | .0118 | .0254 |
| 130 | .0000 | .0002 | .0001 | .0013 | .0017 | .0015 |
| 131 | .0070 | .0023 | .0046 | .0054 | .0072 | .0063 |
| 132 | .0007 | .0003 | .0005 | .0016 | .0019 | .0018 |
| 133 | .0011 | .0005 | .0008 | .0046 | .0053 | .0050 |
| 134 | .0004 | .0007 | .0006 | .0039 | .0139 | .0089 |
| 135 | .0159 | .0047 | .0103 | .0154 | .0037 | .0096 |

**Table 1.**—*Horizontal surface distribution of meteoritic material*—Continued

**Table 1.**—*Horizontal surface distribution of meteoritic material*—Continued

| Location of sample (see fig. 9) | Percent by weight of magnetic material | | | | | |
|---|---|---|---|---|---|---|
| | Size 40 | | | Size 100 | | |
| | In samples | | Average | In samples | | Average |
| 136 | .0015 | .0114 | .0064 | .0221 | .0249 | .0235 |
| 137 | .0003 | .0004 | .0004 | .0025 | .0050 | .0038 |
| 138 | .0002 | .0018 | .0010 | .0089 | .0100 | .0094 |
| 139 | .0065 | .0070 | .0068 | .0318 | .0014 | .0166 |
| 140 | .0010 | .0027 | .0018 | .0004 | .0038 | .0021 |
| 141 | .0016 | .0067 | .0042 | .0158 | .0026 | .0092 |
| 142 | .0002 | .0007 | .0004 | .0037 | — | — |
| 143 | .0000 | .0002 | .0001 | .0009 | .0002 | .0006 |
| 144 | .0017 | .0074 | .0046 | .0037 | .0079 | .0058 |
| 145 | .0012 | .0007 | .0010 | .0022 | .0006 | .0014 |
| 146 | .0049 | .0016 | .0032 | .0003 | .0005 | .0004 |
| 147 | .0010 | .0067 | .0038 | .0172 | .0047 | .0110 |
| 148 | .0012 | .0045 | .0028 | .0006 | .0021 | .0014 |
| 149 | .0045 | .0003 | .0024 | .0028 | .0028 | .0028 |
| 150 | .1760 | .0048 | .0904 | .0269 | — | — |
| 151 | .0244 | .0230 | .0237 | .0292 | .0300 | .0296 |
| 152 | .0018 | .0004 | .0011 | .0005 | .0002 | .0004 |
| 153 | .0067 | .0021 | .0044 | .0047 | .0041 | .0044 |
| 154 | .0933 | .0512 | .0722 | .0121 | .0125 | .0123 |
| 155 | .0061 | .0007 | .0034 | .0049 | .0001 | .0025 |
| 156 | .0001 | .0007 | .0004 | .0059 | .0033 | .0046 |
| 157 | .0023 | .0020 | .0022 | .0088 | .0026 | .0057 |
| 158 | .0000 | .0005 | .0002 | .0012 | .0077 | .0044 |
| 159 | .0039 | .0012 | .0026 | .0159 | .0030 | .0094 |
| 160 | .0013 | .0018 | .0016 | .0007 | .0073 | .0040 |
| 161 | .0088 | .0202 | .0145 | .0096 | .0064 | .0080 |
| 162 | .0003 | .0000 | .0002 | .0022 | .0004 | .0013 |
| 163 | .0003 | .0002 | .0002 | .0013 | .0028 | .0020 |
| 177 | .0009 | .0036 | .0022 | .0030 | .0037 | .0033 |
| 178 | .0125 | .0157 | .0141 | .0068 | .0094 | .0081 |
| 179 | .0113 | .0159 | .0136 | .0038 | .0010 | .0024 |
| 180 | .0118 | .0035 | .0076 | .0072 | .0102 | .0087 |
| 181 | .0157 | .0080 | .0118 | .0235 | .0064 | .0150 |
| 182 | .0191 | .0138 | .0164 | .0030 | .0126 | .0078 |
| 183 | .0004 | .0004 | .0004 | .0024 | .0022 | .0023 |
| 184 | — | — | — | — | — | — |
| 185 | .0032 | .0035 | .0034 | .0011 | .0015 | .0013 |
| 186 | .0056 | .0034 | .0045 | .0097 | .0086 | .0092 |
| 187 | .0017 | .0032 | .0024 | .0015 | .0061 | .0038 |
| 188 | .0043 | .0108 | .0076 | .0048 | .0128 | .0088 |
| 189 | .0231 | .0766 | .0498 | .0127 | .0168 | .0148 |
| 190 | .0017 | .0110 | .0064 | .0020 | .0105 | .0062 |
| 191 | .4830 | .2490 | .3660 | .0314 | .0120 | .0217 |
| 192 | .2160 | .1169 | .1664 | .0285 | .0423 | .0354 |
| 193 | .0158 | .0557 | .0358 | .0072 | .0176 | .0124 |
| 194 | .0042 | .0167 | .0104 | .0083 | .0025 | .0054 |
| 195 | .0376 | .0265 | .0320 | .0028 | .0046 | .0037 |
| 208 | .0083 | .0103 | .0093 | .0171 | .0151 | .0161 |
| 209 | .1595 | .0659 | .1127 | .0241 | .0256 | .0248 |
| 210 | .0087 | .0083 | .0085 | .0023 | .0047 | .0035 |
| 211 | .0523 | .0620 | .0572 | .0213 | .0274 | .0244 |
| 212 | .0307 | .0568 | .0438 | .0071 | .0115 | .0093 |
| 213 | .0057 | .0034 | .0046 | .0311 | .0073 | .0192 |
| 214 | .0035 | .0063 | .0049 | .0052 | .0090 | .0071 |
| 215 | .0045 | .0054 | .0050 | .0050 | .0125 | .0088 |
| 216 | .0189 | .0062 | .0126 | .0046 | .0564 | .0305 |
| 217 | .0009 | .0020 | .0014 | .0038 | .0018 | .0028 |
| 218 | .0008 | .0007 | .0008 | .0006 | .0005 | .0006 |
| 219 | .0017 | .0029 | .0023 | .0053 | .0052 | .0052 |
| 220 | .0002 | .0007 | .0004 | .0011 | .0040 | .0026 |
| 221 | .0180 | .0147 | .0164 | .0187 | .0032 | .0110 |
| 222 | .0065 | .0013 | .0039 | .0053 | .0100 | .0076 |
| 223 | .0024 | .0003 | .0014 | .0050 | .0014 | .0032 |
| 224 | .0005 | .0017 | .0011 | .0016 | .0009 | .0012 |
| 225 | .0000 | .0000 | .0000 | .0003 | .0014 | .0008 |
| 226 | .0008 | .0005 | .0006 | .0005 | .0015 | .0010 |
| 227 | .0125 | .0002 | .0064 | .0001 | .0007 | .0004 |
| 228 | .0042 | .0005 | .0024 | .0054 | .0042 | .0048 |
| 229 | .0010 | .0039 | .0025 | .0061 | .0035 | .0048 |
| 230 | .0020 | .0025 | .0022 | .0036 | .0044 | .0040 |
| 231 | .0009 | .0002 | .0006 | .0011 | .0007 | .0009 |
| 232 | .0005 | .0003 | .0004 | .0012 | .0016 | .0014 |
| 233 | .0288 | .0269 | .0278 | .0053 | .0185 | .0119 |
| 234 | .0001 | .0017 | .0009 | .0003 | .0005 | .0004 |
| 235 | .0154 | .0172 | .0163 | .0084 | .0115 | .0100 |
| 236 | .0003 | .0000 | .0002 | .0007 | .0009 | .0008 |
| 237 | .0203 | .0129 | .0166 | .0248 | .0040 | .0144 |
| 238 | .0117 | .0056 | .0086 | .0107 | .0048 | .0078 |
| 239 | .0090 | .0110 | .0100 | .0022 | .0178 | .0100 |
| 240 | .0032 | .0023 | .0028 | .0023 | .0034 | .0028 |
| 241 | .0099 | .0072 | .0086 | .0065 | .0060 | .0062 |
| 242 | .0023 | .0040 | .0032 | .0061 | .0042 | .0052 |
| 243 | .0068 | .0066 | .0067 | .0096 | .0069 | .0082 |
| 244 | .0013 | .0015 | .0014 | .0119 | .0057 | .0088 |
| 245 | .0019 | .0016 | .0018 | .0132 | .0196 | .0164 |
| 246 | .0065 | .0081 | .0073 | .0462 | .0262 | .0362 |
| 247 | .0006 | .0006 | .0006 | .0104 | .0026 | .0065 |
| 248 | .0001 | .0002 | .0002 | .0003 | .0007 | .0005 |
| 249 | .0001 | .0007 | .0004 | .0058 | .0030 | .0044 |
| 250 | .0005 | .0023 | .0014 | .0017 | .0013 | .0015 |
| 251 | .0066 | .0066 | .0066 | .0065 | .0140 | .0102 |
| 252 | .0109 | .0086 | .0098 | .0094 | .0148 | .0121 |
| 253 | .0188 | .0056 | .0122 | .0349 | .0409 | .0379 |
| 254 | .0142 | .0083 | .0112 | .1361 | .0728 | .0994 |
| 255 | .0039 | .0063 | .0050 | .0925 | .0464 | .0694 |
| 256 | .0006 | .0007 | .0006 | .0015 | .0014 | .0014 |
| 257 | .0013 | .0036 | .0025 | .0029 | .0016 | .0022 |
| 258 | .0225 | .0390 | .0308 | .0257 | .0089 | .0173 |
| 259 | .0065 | .0008 | .0036 | .0088 | .0008 | .0048 |
| 260 | .0002 | .0011 | .0006 | .0036 | .0027 | .0032 |
| 261 | .0005 | .0027 | .0016 | .0029 | .0166 | .0098 |
| 262 | .0112 | .0080 | .0096 | .0098 | .0226 | .0162 |
| 263 | .0068 | .0042 | .0055 | .0215 | .0059 | .0137 |
| 264 | .0114 | .0106 | .0060 | .0041 | .0041 | .0041 |
| 265 | .0370 | .0329 | .0350 | .0046 | .0131 | .0088 |
| 266 | .0023 | .0027 | .0025 | .0039 | .0042 | .0040 |
| 267 | .0018 | .0042 | .0030 | .0023 | .0038 | .0030 |
| 268 | .0014 | .0025 | .0020 | .0020 | .0047 | .0034 |
| 269 | .0032 | .0014 | .0023 | .0010 | .0026 | .0018 |
| 270 | .0035 | .0022 | .0028 | .0040 | .0033 | .0036 |
| 271 | .0008 | .0014 | .0011 | .0007 | .0014 | .0010 |
| 272 | .0055 | .0106 | .0080 | .0062 | .0062 | .0062 |
| 273 | .0182 | .0203 | .0192 | .0123 | .0073 | .0098 |
| 274 | .0099 | .0093 | .0096 | .0094 | .0130 | .0112 |
| 275 | .0098 | .0116 | .0107 | .0113 | .0262 | .0188 |
| 276 | .0080 | .0044 | .0062 | .0050 | .0080 | .0065 |
| 277 | .0171 | .0113 | .0142 | .0123 | .0242 | .0182 |
| 278 | .0264 | .0162 | .0213 | .0212 | .0171 | .0192 |
| 279 | .0042 | .0093 | .0068 | .0082 | .0026 | .0054 |
| 280 | .0180 | .0118 | .0149 | .0093 | .0050 | .0072 |
| 281 | .0024 | .0172 | .0098 | .0474 | .0296 | .0385 |
| 282 | .0114 | .0043 | .0078 | .0398 | .0189 | .0294 |
| 283 | .0214 | .0165 | .0190 | .0196 | .0320 | .0258 |
| 284 | .0049 | .0187 | .0118 | .0162 | .0072 | .0117 |
| 285 | .0171 | .0042 | .0106 | .0302 | .0229 | .0266 |
| 286 | .0064 | .0174 | .0119 | .0158 | .0069 | .0114 |
| 287 | .0098 | .0100 | .0099 | .0162 | .0276 | .0219 |
| 288 | .0066 | .0154 | .0110 | .0224 | .0321 | .0272 |
| 289 | .0133 | .0115 | .0124 | .0193 | .0140 | .0166 |
| 290 | .0057 | .0043 | .0050 | .0028 | .0063 | .0046 |
| 291 | .0074 | .0109 | .0092 | .0079 | .0042 | .0060 |
| 292 | .0050 | .0050 | .0050 | .0077 | .0074 | .0076 |
| 293 | .0082 | .0085 | .0084 | .0090 | .0304 | .0197 |
| 294 | .0009 | .0024 | .0016 | .0099 | .0132 | .0116 |
| 295 | .0092 | .0069 | .0080 | .0050 | .0063 | .0056 |
| 296 | — | — | — | — | — | — |
| 297 | .0623 | .0197 | .0410 | .0093 | .0284 | .0188 |
| 298 | .0117 | .0340 | .0228 | .0181 | .0052 | .0116 |
| 299 | .0032 | .0094 | .0063 | .0377 | .0334 | .0356 |
| 300 | .0060 | .0060 | .0060 | .0306 | .0231 | .0268 |
| 301 | .0058 | .0272 | .0165 | .0396 | .0545 | .0470 |
| 302 | .0049 | .0085 | .0067 | .0432 | .0206 | .0319 |
| 303 | .0066 | .0080 | .0073 | .0035 | .0083 | .0059 |
| 304 | .0031 | .0049 | .0040 | .0083 | .0022 | .0052 |
| 305 | .0035 | .0017 | .0026 | .0039 | .0047 | .0043 |
| 306 | .0196 | .0095 | .0146 | .0068 | .0294 | .0181 |
| 307 | .0037 | .0121 | .0079 | .0074 | .0174 | .0124 |
| 308 | .0140 | .0241 | .0190 | .0040 | .0030 | .0035 |
| 309 | .0048 | .0038 | .0043 | .0021 | .0020 | .0020 |
| 310 | .0152 | .0190 | .0171 | .0027 | .0113 | .0070 |
| 311 | .0344 | .0146 | .0245 | .0047 | .0000 | .0024 |
| 312 | .0005 | .0009 | .0007 | .0007 | .0007 | .0007 |
| 313 | .0100 | .0037 | .0068 | .0053 | .0123 | .0088 |
| 314 | .0075 | .0100 | .0088 | .0076 | .0058 | .0067 |
| 315 | .0021 | .0072 | .0046 | .0056 | .0079 | .0068 |
| 316 | .0013 | .0000 | .0006 | .0057 | .0016 | .0036 |
| 317 | .0026 | .0104 | .0065 | .0038 | .0013 | .0026 |
| 318 | .0016 | .0081 | .0048 | .0039 | .0067 | .0053 |
| 319 | .0012 | .0022 | .0017 | .0076 | .0051 | .0064 |
| 320 | .0129 | .0034 | .0082 | .0151 | .0099 | .0125 |
| 321 | .0029 | .0052 | .0040 | .0017 | .0021 | .0024 |
| 322 | .0045 | .0002 | .0024 | .0022 | .0011 | .0016 |
| 323 | .0005 | .0002 | .0004 | .0008 | .0008 | .0008 |
| 324 | .0040 | .0006 | .0023 | .0050 | .0024 | .0037 |
| 325 | — | — | — | — | — | — |

TABLE 2.—*Distribution of meteoritic material in vertical shafts*

| Location of sample | Depth (inches) | Percent by weight | |
|---|---|---|---|
| | | Size 40 | Size 100 |
| 164 | 0 | .5600 | .0302 |
| | 2 | .3500 | .1080 |
| | 12 | .0590 | .0408 |
| | 24 | .0084 | .0057 |
| 165 | 0 | .0035 | .0160 |
| | 2 | .0033 | .0021 |
| | 12 | .0011 | .0188 |
| | 30 | .0017 | .0057 |
| 166 | 0 | .0748 | .0589 |
| | 2 | .1600 | .0771 |
| | 18 | .0118 | .0054 |
| | 33 | .0054 | .0163 |
| 167 | 0 | .3930 | .0207 |
| | 1 | .2050 | .0274 |
| | 6 | .1400 | .0288 |
| | 15 | .0455 | .0043 |
| 168 | 0 | .2220 | .0128 |
| | 1 | .0788 | .0459 |
| | 6 | .1360 | .0150 |
| 169 | 0 | .0834 | .0337 |
| | 1 | .0630 | .0224 |
| | 12 | .0036 | .0036 |
| | 21 | .0054 | .0048 |
| 170 | 0 | .0320 | .0431 |
| | 1 | .0435 | .0139 |
| | 25 | .0033 | .0168 |
| | 54 | .0002 | .0042 |
| 171 | 0 | .0032 | .0234 |
| | 1 | .0603 | .0286 |
| | 12 | .0274 | .0066 |
| | 27 | .0013 | .0008 |
| 172 | 0 | .0054 | .0036 |
| | 1 | .0056 | .0050 |
| | 15 | .0003 | .0014 |
| | 33 | .0001 | .0009 |
| 173 | 0 | .1295 | .0411 |
| | 1 | .0810 | .0241 |
| | 13 | .0756 | .0180 |
| | 27 | .0635 | .0137 |
| 174 | 0 | .1654 | .0695 |
| | 1 | .0924 | .0458 |
| | 18 | .0430 | .0088 |
| | 39 | .0250 | .0054 |
| 175 | 0 | .0179 | .0141 |
| | 1 | .0103 | .0143 |
| | 12 | .0036 | .0016 |
| | 39 | .0018 | .0008 |
| 176 | 0 | .0736 | .0132 |
| | 1 | .0570 | .0144 |
| | 9 | .0378 | .0104 |
| 196 | 0 | .0751 | .0250 |
| | 1 | .0990 | .0134 |
| | 15 | .1630 | .0195 |
| | 30 | .1425 | .0174 |
| 197 | 0 | .1748 | .0668 |
| | 1 | .0903 | .0104 |
| | 9 | .0171 | .0384 |
| | 18 | .0426 | .0023 |
| 198 | 0 | .1218 | .0307 |
| | 1 | .1031 | .0150 |
| | 21 | .0039 | .0013 |
| | 42 | .0032 | .0043 |
| 199 | 0 | .0297 | .0060 |
| | 1 | .0081 | .0049 |
| | 7 | .0080 | .0117 |
| 200 | 0 | .0072 | .0017 |
| | 1 | .0101 | .0027 |
| | 9 | .0069 | .0036 |
| 201 | 0 | .0052 | .0124 |
| | 1 | .0048 | .0075 |
| | 6 | .0103 | .0144 |
| | 15 | .0164 | .0536 |
| 202 | 0 | .0212 | .0117 |
| | 1 | .0122 | .0099 |
| | 18 | .0010 | .0007 |
| | 36 | .0008 | .0030 |
| 203 | 0 | .0105 | .0307 |
| | 1 | .0221 | .0053 |
| | 13 | .0223 | .0033 |
| 204 | 0 | .0287 | .0209 |
| | 1 | .0060 | .0141 |
| | 18 | .0006 | .0005 |
| | 45 | .0066 | .0021 |
| 205 | 0 | .0064 | .0013 |
| | 1 | .0012 | .0031 |
| | 9 | .0030 | .0006 |
| 206 | 0 | .0007 | .0011 |
| | 1 | .0000 | .0005 |
| | 11 | .0000 | .0000 |
| 207 | 0 | .0012 | .0016 |
| | 1 | .0001 | .0003 |
| | 5 | .0000 | .0000 |

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